Continuous Structural Monitoring of Oil Rig Sub-Sea Structures for Flooded Member Detection Using Underwater Ultrasound

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Abstract. An underwater ultrasound system for detecting flooding in the hollow sub-sea structures of offshore steel oil-rigs is presented. A sensor, attached to a sub-sea structure and powered by seawater, transmits underwater ultrasound chirp-encoded signals to a real-time digital signal processing monitoring system at surface level. Experiments performed using a jointed steel pipe structure 1 ton in weight, with dimensions of 7 m × 0.5 m × 16 mm, completely immersed in seawater showed excellent performance using a central excitation frequency of 38 kHz, over distances of 100 m.

1. Introduction

Sub-sea structures used in offshore steel platforms are normally made from sealed hollow steel pipes [1]. The ingress of water into the pipes due to wall cracking is a serious issue, leading to impaired structural performance and the onset of corrosion. This critical matter is used as the basis for an inspection method known as flooded member detection (FMD). The advantage of this method is the capability of not only identifying any member with through-thickness cracks regardless of its location in the length of the member, but also providing a rapid screen check (whilst acknowledging that cracks of through-thickness dimensions do not make the integrity of the structure unacceptable) [2]. Underwater nondestructive testing (NDT) methods such as X-ray imaging systems and ultrasonic arrays [3] have been conventionally used for flood detection. Reasonably good results are produced; however, these techniques are expensive to employ on a regular basis and demand special enclosures and strict safety precautions, requiring the deployment of a diver or a remotely operated vehicle (ROV).

As an alternative, an autonomous and continuous monitoring ultrasonic sensor system is now being developed, which is permanently attached to the inner wall of the lower attachment point of a sub-sea beam, and whose long-life battery, normally inert, is activated by the ionic action of the seawater. Upon activation, the sensor transmits an encoded signal to a hydrophone, mounted in a permanent location close to the water's surface. The encoded signal provides information to a base receiving station on the location of the sensor and hence the flooded member.

Work has been conducted by the authors using ultrasound encoded signals, based on two possible communication media: either steel or seawater; the former, exploiting the guide-wave effect provided by the steel jacket structure [4, 5]; the latter, taking advantage of the relative ease of propagation of underwater low-frequency ultrasound [6]. In this paper the underwater approach is addressed. This work presents the results obtained from an underwater system composed of a waterproof microcontroller-based transmitter, a signal booster, a single PZT transducer and a 9V seawater activated battery package. The receiver instrumentation package comprises a PZT transducer, an amplifier, a real-time digital signal processing (DSP) system, a digital oscilloscope and a computer.

Experiments were performed using a jointed steel pipe structure 1 ton in weight, 7 m $\times$ 0.5 m $\times$ 16 mm in dimension, completely immersed in seawater and separated from the receiver by 100 m. Chirp-encoded pulses of 8 kHz bandwidth with a central frequency 38 kHz were transmitted in conjunction with signal processing algorithms at the receiver. Firstly, these pulses were matched with a suitable finite impulse response (FIR) filter and secondly with a very narrow bandwidth infinite impulse response (IIR) filter. Although the attenuation in this approach was predominantly geometric in origin, the results obtained displayed clear signal identification with signal to noise ratios (SNRs) of 14.8 dB and 15.4 dB for the FIR and IIR algorithms respectively, with a battery drive voltage of 9 V.

2. Theory

Ultrasonic energy is generated and received by transducers or probes that make use of the piezoelectric effect; these convert acoustic energy to or from types of energy such as electrical, mechanical and thermal. For a given transducer, the applied voltage determines the amplitude of the generated ultrasound wave. In this instance, 9 Volts batteries were employed in the assessment of the system. All ultrasound transducers produce sound fields that diverge in the far field; in this application, the divergence was of the order of 23^{o} at –3dB, which causes attenuation, mainly geometric in origin.

Acoustic impedance, Z_a, defined as the product of density δ and sound velocity c, determines the transmission and reflection of sound energy between two different materials. This is also a source of signal attenuation and it is covered in the next topic.

2.1 Underwater communication channel

An extensively used conventional communication system model is the source, path and receiver configuration; where, for this approach, ultrasound transducers act as source and receiver respectively, and steel and seawater comprise the transmission channel for the remote system. Various and significant restrictions imposed on this signal channel exist, the most serious of which are noise and signal attenuation, leading to poor SNR.

Mismatched acoustic impedance between steel and water is an important consideration which leads to reflection of waves and thereby attenuation. In addition to the single interface between two materials of large dimensions, the double interface, as in the case of plates immersed in water, is of interest in this application. If the incident wave is of unlimited length, the waves are intensified or weakened, depending on the phase position. The reflection, R, and transmission, T, coefficients can be obtained considering the plate thickness, d, the wavelength in the plate material, λ, and using the ratio, m, of the acoustic impedances of steel and water. The minima of R and maxima of T are periodical; consequently, their values oscillate regularly between fixed limits with increasing thickness. In this application, having a fixed thickness and considering steel pipes of large diameters as plates, the selection of the frequency determines the transmission coefficient. The first minimum R and maximum T occurs at $d/\lambda = 0$ [7]; therefore, selecting the lowest frequency as the one which yields the best transmission coefficient. It was estimated that approximately 12 % of the signal would be transmitted using a pipe of 16 mm in thickness and a frequency of 38 kHz.

Limitations due to the medium are an important consideration, since this largely controls the signal-to-noise ratio. It is reported that for signals below 100 kHz, this may be noise due to the sea state; however, above 100 kHz it is essentially thermal noise resulting from the molecular agitation of water [8]. Absorption of sound energy in the sea increases with frequency and distance and is dependent on the local temperature and salinity. However, the lower the chosen signal frequency, the smaller the possible bandwidth that can be attained with the ultrasound transducers. Taking into consideration these restrictions, the selected central frequency for driving the ultrasound transducers was 38 kHz.

2.2 Signal selection

A signal channel that presents low power output, limited bandwidth, and absorption and noise difficulties resembles a problem encountered with radar [9]. To overcome this problem, an excitation signal widely used in radar was selected, namely the pulse compressed signal, also known as the chirp signal.

Long pulses of constant carrier frequency possess narrow bandwidths and thereby poor resolution properties. Nevertheless, introducing frequency modulation in these long signals, the bandwidth can be broadened considerably. When the modulated pulse uses a linear frequency sweep, it is known as the chirp pulse [9]. Moreover, it has been shown that square chirps, used in ultrasonic NDT pulse-echo modes, not only increases the energy of the signal in the transmitter, thereby improving the SNR, but also reduces the complexity of the hardware for signal generation [10]. It is not necessary to use digital-to-analogue converters to generate square chirps; even power amplifiers can be substituted by high speed switching circuits. Therefore, square chirps of 8 kHz bandwidth (34 kHz – 42 KHz) were implemented.

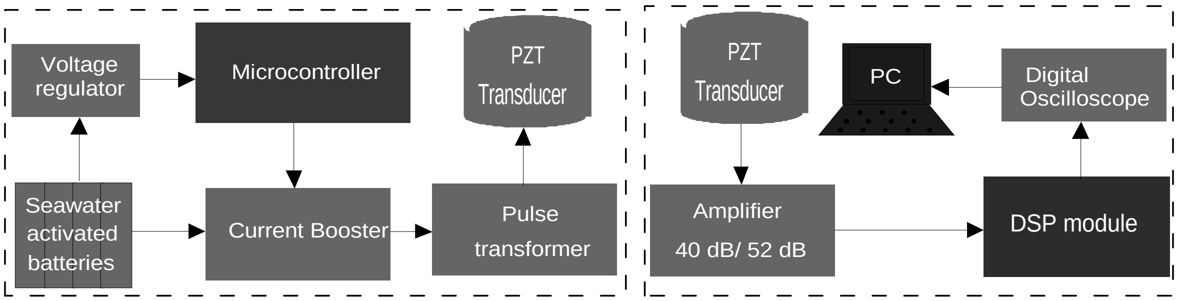
3. Underwater ultrasound system

3.1 Transmitter design

A waterproof transmitter sensor was designed to generate square chirps from the internal wall of a steel pipe immersed and flooded by seawater. Its principal components are shown in Figure 1a. They are a microcontroller, a signal booster, a longitudinal PZT transducer and a seawater activated battery package. A square chirp of 8 kHz bandwidth (34 kHz - 42 kHz), pulse width of 18ms and Pulse Position Modulation (PPM) of 300 ms, as encoding selection, was programmed in the internal flash memory of the microcontroller. The digital signal was fed to a pulse transformer and connected in a step up mode of ratio 1:8, to boost the signals up to 50V. This signal was applied to the actual PZT transducer. Commercial 9V seawater activated batteries were used to power up the sensor.

3.2 Receiver design

The receiver instrumentation, whose main components are shown in Figure 1b, is based on a real time DSP system and a PZT transducer. Underwater chirp pulses were amplified and filtered in real-time. Digital FIR band pass filters of 8 kHz bandwidth (34 kHz- 42 kHz) and an IIR super-narrow band pass filter (38.3 kHz – 38.6 kHz) were designed to operate with the transmitted chirp signals. The filtered signals were digitised using a Tektronix digital oscilloscope with data length of 2500 samples and transferred via an RS-232 interface to a computer where they were stored.

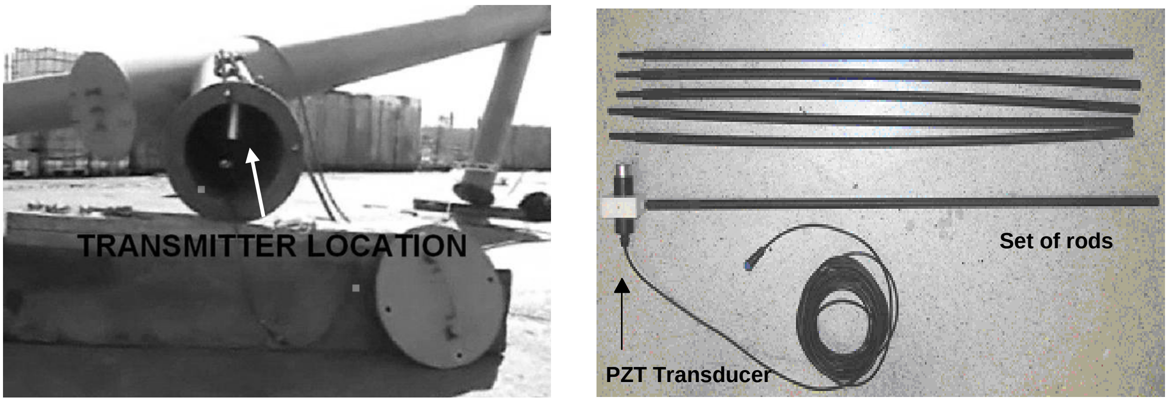


a) b)

Figure 1. Underwater ultrasound system showing their instrumentation main components; a) transmitter and b) receiver.

4. Experiment set up

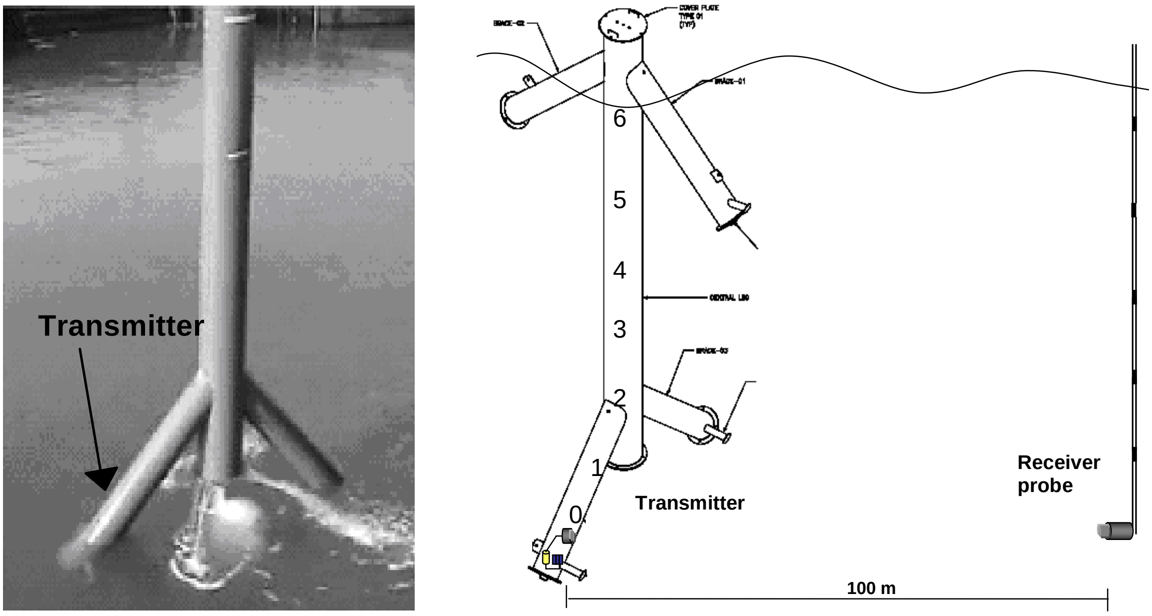
Experiments were conducted in a naval dockyard using a jointed steel pipe structure, 7 m in length, 0.5m in diameter and 16mm in thickness, completely immersed (vertically) in seawater. The jointed pipe structure had holes in it to allow ingress of seawater into the pipe to activate the battery. The transmitter was attached to the inner wall of a spur pipe using a mechanical jack as depicted in Figure 2a; and the receiver, a PZT transducer, was attached to a set of rods that were assembled to obtain the required length; Figure 2b depicts this transducer and the rods.



a) b)

Figure 2. a) Transmitter location; b) receiving transducer and a set of rods

Figure 3a depicts the steel structure being immersed in seawater. The receiving transducer was also immersed in the seawater and moved away from the jointed pipe as depicted in Figure 3b. The maximum separation between transducers was approximately 100 m. The received signals were conveyed via a 100 m coaxial cable to the instrumentation receiver system located in a van.



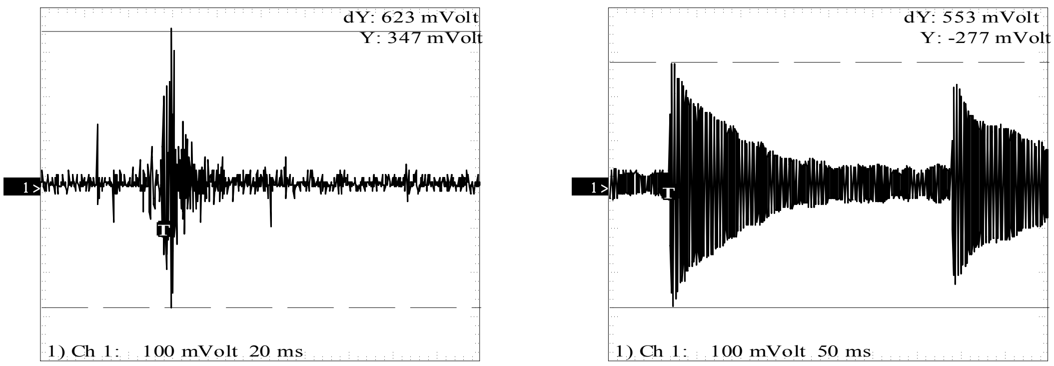
a) b)

Figure 3. Experimental setup using a jointed steel pipe structure, 7m x 0.5m x 16mm; a) being immersed in seawater; b) receiver and transmitter transducers separation.

5. Results

The underwater ultrasound system for FMD was tested by immersing the jointed steel structure completely in seawater and flooded for sensor activation. The transmitter was programmed to generate the chirp signal. Nevertheless, in order to de-noise the received signals and improve the SNR, two different real time digital filters, FIR and IIR, were evaluated and configured in the receiver.

Received signals using the FIR and IIR filters and separation distances between the transducers of approximately 40 m and 100 m respectively are shown in Figure 4. Both types of filtering allowed clear signal identification with SNRs of 14.8 dB and 15.4 dB for the FIR and IIR algorithms respectively.



a) b)

Figure 4. Typical signals detected in the underwater ultrasound FMD system using a 34 kHz – 42 kHz chirp, with the structure immersed to a depth of 6 m; a) original received signal at 40 m and an amplitude of 3.09 μV, processed by an FIR filter; (b) original received signal at 100 m and an amplitude of 650 nV, processed by an IIR filter.

Measured over 40 m, the attenuation was calculated to be 0.8 dBm^{-1}. Considering the maximum separation distance in the trial was approximately 100 m, with an initial reading taken at 5 m, the attenuation figure was calculated to be 0.4 dBm^{-1}; by increasing the power of the transmitter by a factor of 3, it is estimated that a detection range of 200 m distance could be achieved, with otherwise no modification to the system.

6. Discussion

The feasibility of using permanently attached intelligent sensors to monitor the flooding of structural sub-sea members in offshore oilrigs has been demonstrated experimentally. The system uses a low-cost standalone waterproof sensor design based on microcontroller and a single PZT transducer which is powered by seawater activated batteries. It takes advantage of the relative ease of propagation of the underwater low-frequency ultrasound. Dependent upon the imposed channel restrictions, chirp square (34 kHz – 42 kHz) encoded transmissions of 50V, were successfully generated and acquired by an instrumentation receiver based on a real-time DSP system and a single PZT transducer. The SNR was improved via the flexible design and implementation of digital, sharp cut-off, IIR and FIR filters. As a first attempt, the transmitted information was encoded using PPM by varying the mark-space of transmitted pulses. The attained gross attenuation value of 0.8 dBm^{-1} and 0.4 dBm^{-1} using chirps signals and FIR and IIR filter respectively, is an encouraging result.

Furthermore, due to the fact that the attenuation in this case is predominantly geometric in origin, losses could also be minimised by increasing the diameter of the transmitting transducer, since the beam spread is an inverse function of the diameter of the active face. Improvements in terms of SNR can be achieved by replacing the PZT transducer technology employed in the receiver by a PDVF transducer hydrophone, which offers not only better receiver efficiency than PZT materials, but also presents a lower acoustic mismatch with water, which enhances their performance.

7. Conclusion

An underwater ultrasound system for the intention of detecting flooded sub-sea members of oil rigs has been designed, implemented and evaluated. Successful transmissions and reception of encoded information, using PPM, has been achieved. Chirp pulses and real time digital FIR and IIR filtering attained significant SNRs; in this immersion test, however, IIR filter presented marginally better performance. The system represents a potential alternative low cost and safe solution to current underwater NDT approaches. These results are very encouraging, taking the authors to the next stage of this work, which is to carry out tests on a commercial offshore platform or in a structure of such dimensions.

Acknowledgements

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